

Electrostatic Accelerators

Single-Stage accelerators (Cockcroft-Walton Machines)

Cockcroft-Walton machines are the simplest types of accelerators. They are based on passing ions through sets of aligned electrodes that are operated at successively higher fixed potentials. Usually, voltage-doubling circuits are used for generating the high electric fields.

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A machine consists of an ion source (often hydrogen gas) located at one end, and a target at the other, with the electrodes arranged in between. First, electrons can either be added to or stripped from the atoms of interest in order to produce ions, which are then passed through the series of accelerating regions. The kinetic energy gained by an ion of charge q , passing through the voltage difference V , is given simply by $T = qV$. John Cockcroft and Ernest Walton were the first to successfully apply these principles to particle acceleration, and used their device to disintegrate lithium nuclei using protons of about 400 keV.

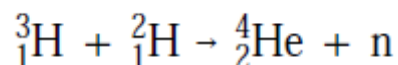
Cockcroft-Walton accelerators are still used for obtaining "low" kinetic energies, up to 4 MeV for protons. Presently, such accelerators are used in many installations as the first stage of acceleration, injector, in a more complex machine designed to produce high energy beams.

In a single-stage accelerator, such as a Cockcroft-Walton type, the total potential produced from a high voltage generator is imposed across the accelerator, i.e. between the ion source and the target. The kinetic energy, E_{kin} , of the projectile is:

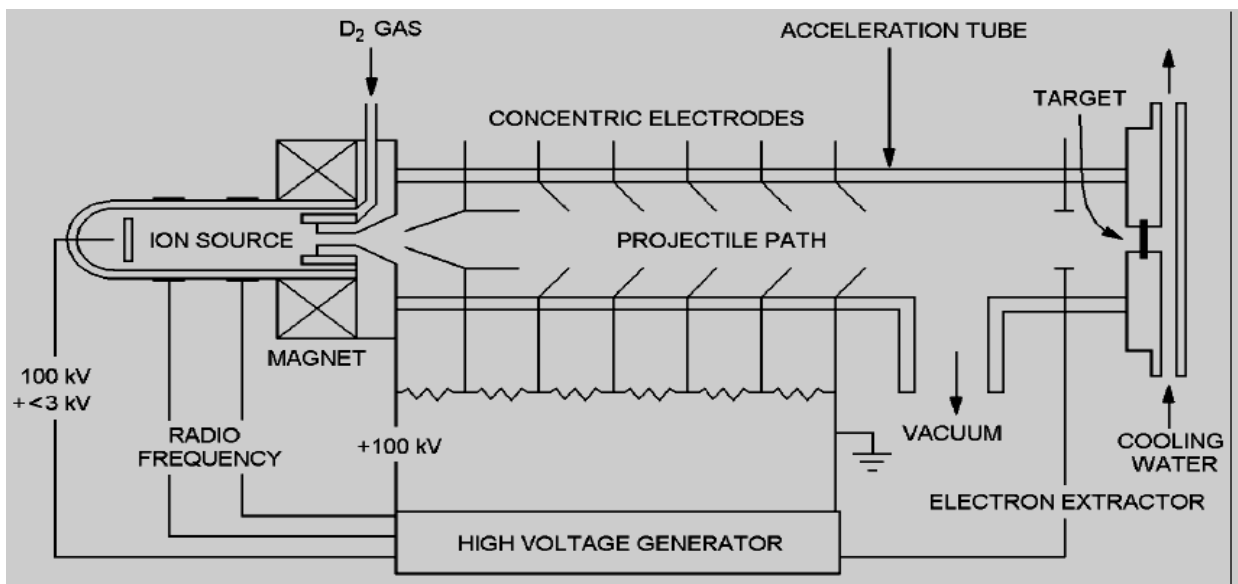
$$E_{\text{kin}} = nqV$$

where q is the charge of the accelerated ions (Coulomb) and V is the imposed potential across the acceleration gap. This equation is identical to (2.5) except that n is the number of accelerating stages ($n = 1$ for the Cockcroft-Walton machine).

In recent years small and relatively inexpensive accelerators have come into use based on the Cockcroft-Walton principle. These are known as transformer-rectifier accelerators and are primarily used for acceleration of electrons or acceleration of deuterons for production of neutrons through the reaction:



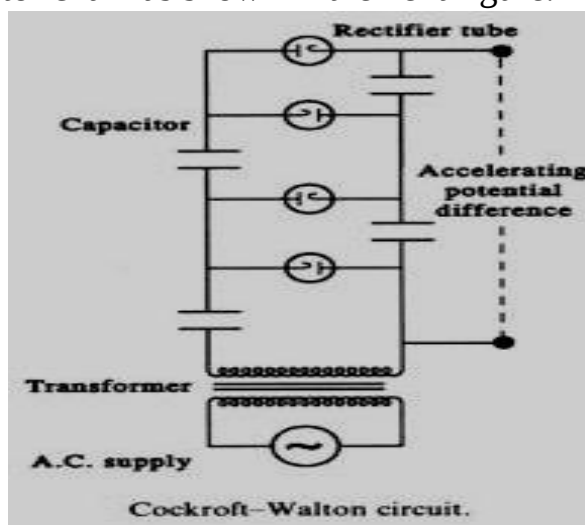
Tritium targets are bombarded by accelerated deuterons. Tunneling of the Coulomb barrier results in a good yield for this reaction even for energies of 0.1 MeV.



Principle of a single-stage linear accelerator. The D_2 gas enters the vacuum through a palladium membrane.

Next figure illustrates an inexpensive transformer-rectifier type accelerator. Deuterium molecules leak through a heated palladium foil into the vacuum of the ion source, where a high frequency electric field decomposes the deuterium molecules to form plasma of D^{+1} ions and electrons. The deuterium ions are extracted from the ion source with a relatively low negative potential to enter the acceleration tube with approximately 2.5 keV kinetic energy.

The voltage difference of 100 kV across the acceleration space is obtained from a transformer and rectifier unit coupled to a set of cylindrical electrodes connected by a resistor chain as shown in the next figure.



The cylindrical electrodes serve the purpose both of acceleration and of focusing the ion beam into the proper path. As the beam particles exit from the last electrode they drift through a short tube and strike the target, which consists of a metal foil covered with titanium in which tritium has been absorbed. Approximately 200 GBq of tritium can be absorbed as titanium tritide on an area of 5 cm². The target is cooled by water to minimize tritium evaporation. The passage of the beam through the target also results in the emission of electrons which are removed by attraction to an anode to avoid interference with the beam.

With a voltage of 100 kV and an ion current of 0.5 mA, this accelerator can produce approximately 10^{10} n s⁻¹ with energy of 14 MeV. It is often desirable to reduce the kinetic energy of these neutrons to thermal values since thermal neutrons have a much larger probability of interacting with target nuclei. Moderation of the neutrons to thermal energies (≈ 0.025 eV) can be accomplished by placing water or paraffin around the target. The flux of the thermal neutrons is relatively low, on the order of 10^8 n cm⁻² s⁻¹. However, the production rate of neutrons increases as the beam energy and beam current increases.

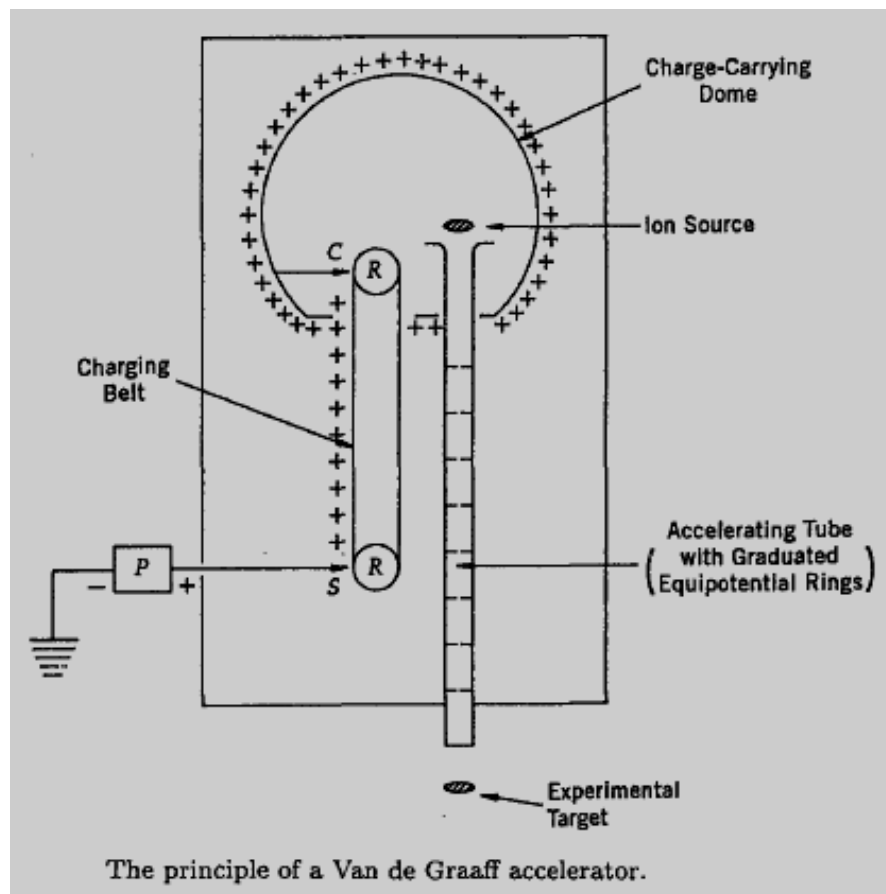
Small accelerators of similar design are commercially available with such dimensions that they can be lowered into bore-holes for in situ neutron activation analysis during gas or oil prospecting.

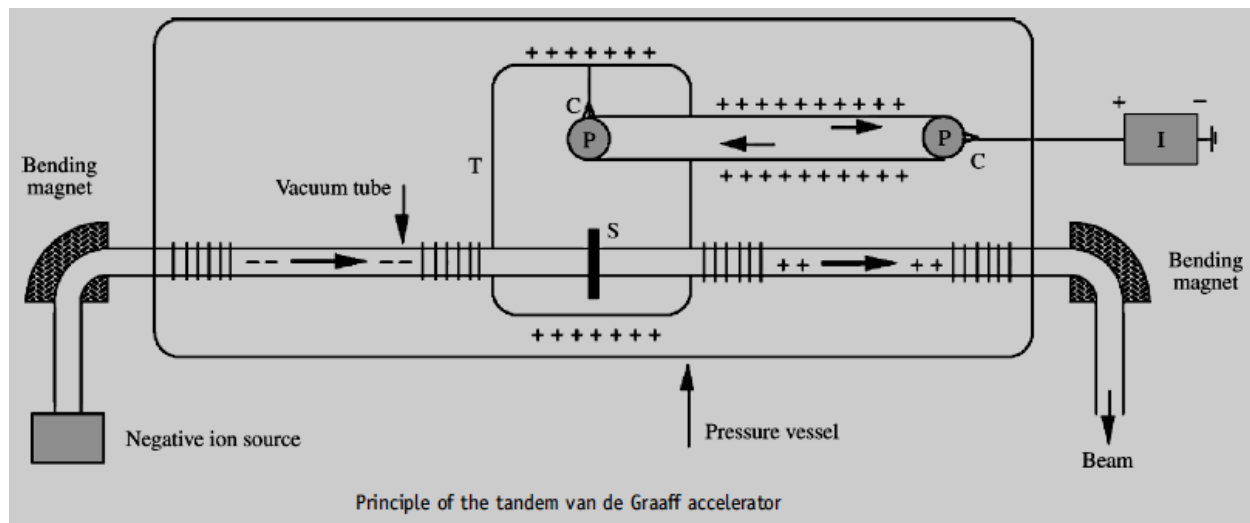
More advanced designs of this type of accelerator use coupling of transformers, rectifiers, and condensers to increase the voltage. With the larger single-stage accelerators it is possible to obtain beams of protons and deuterons which have energies of several MeV and currents of about 10 mA.

Van de Graaff Accelerator

The energy gained by a particle (ion) accelerated in a DC voltage machine is directly proportional to the applied voltage; consequently, clever construction of the high voltage source is of crucial importance. That is precisely what the Van de Graaff generator (named after Robert Van de Graaff) does. The basic principle relies on the fact that since the charge on any conductor resides on its outermost surface, if a conductor carrying charge touches another conductor that envelops it, then, irrespective of its potential, it will transfer all its charge to the outer conductor. This can be used to advantage to increase the charge on any conductor, and consequently to create a higher voltage.

In the Van de Graaff accelerator, charge is carried on a conveyor belt into a large metallic dome, where it is picked off, as shown in next figure. The conveyor belt is made of insulating material, and goes over motor-driven rollers (R). A "sprayer" (S), connected to discharge-voltage terminal, sprays positive ions to the conveyor belt (electrons go to P). (Basically, the high voltage ionizes the gas, and the ions are collected on the conveyor belt.) The points where charges are sprayed or injected onto the belt are known as corona points. The conveyor belt takes the positive charges up to the dome, which is maintained at a positive voltage. The energy needed to do this work is provided by the motors. At the upper end of the conveyor there is a collector C, which collects the positive charges transferred to the dome. Typically, this technique can produce accelerating potentials of up to ≈ 12 MV. (A tandem generator is a modification of the Van de Graaff generator, where negative ions that enter the accelerating tube from one side, are first accelerated to the positive HV terminal, where they are stripped and made positive, and then accelerated as positive ions down to ground potential on the other side of the terminal. This, effectively, doubles the acceleration energy to <25 MeV.)





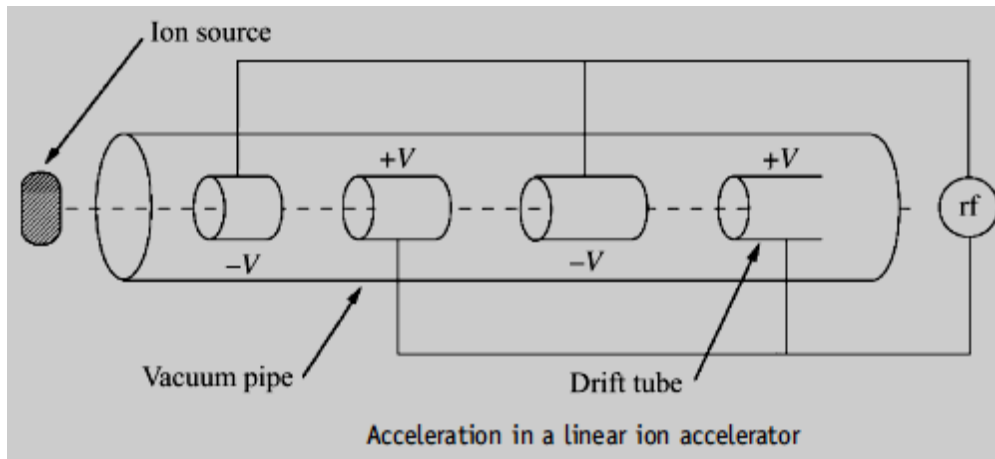
In the last figure, a high voltage source at I passes positive ions to a belt via a comb arrangement at C. The belt is motor driven via the pulleys at P and the ions are carried on the belt to a second pulley where they are collected by another comb located within a metal vessel T. The charges are then transferred to the outer surface of the vessel, which acts as an extended terminal. In this way a high voltage is established on T. Singly-charged negative ions are injected from a source and accelerated along a vacuum tube towards T. Within T there is a stripper S (for example a thin carbon foil) that removes two or more electrons from the projectiles to produce positive ions. The latter then continue to accelerate through the second half of the accelerator increasing their energy still further and finally may be bent and collimated to produce a beam of positive ions. This brief account ignores many technical details.

Resonance Accelerators

Multiple-stage linear accelerator (Linac or Linear Accelerator)

Linear accelerators, as the name implies, accelerate particles along linear trajectories rather than in circular orbits. These accelerators are also based on the resonance principle, and operate as follows. A series of metal tubes, called drift tubes, are located in a vacuum vessel and connected successively to alternate terminals of a radio frequency oscillator, as shown in next figure. Let us suppose that at some time the fields are as shown in the figure. Positive ions from the source will then be accelerated by the electric field towards the first drift tube. If the alternator can change its direction before the ions pass through that tube, then they will be accelerated again on their way between the exit of the first and entry into the second tube, and so on. However, as the particles accelerate, their velocities increase, and consequently, if the drift tubes are all of the same length,

the phase between the particle positions and the potentials at the next tube may not keep in step (that is, the next gap may not accelerate). To avoid this, the drift tubes are made longer along the path so that one radio-frequency (RF) alternator can accelerate the particles all the way to the end.



Because electrons become relativistic at relatively low energies, electron linear accelerators act on a slight variation of the principle just described. The electron source is usually a hot wire filament which, effectively, boils off electrons. These are accelerated through a positive potential grid and rapidly become relativistic. Bunches of these electrons are then passed through accelerating tubes that are fed with microwave power delivered by klystron amplifiers. Electrons radiate easily as they get accelerated, and therefore much power is needed to increase their energy. This power is supplied by the microwave fields that travel in step with electrons in specially shaped iris-loaded waveguides. The longest linear accelerator is the two-mile Stanford Linac (SLAC), and it accelerates electrons to energies of 50 GeV. It is over 3km long.

An ingenious way of reducing the enormous lengths of high-energy linacs has been developed at the Continuous Electron Beam Accelerator Facility (CEBAF) at the Jefferson Laboratory in the USA. This utilizes the fact that above about 50MeV, electron velocities are very close to the speed of light and thus electrons of very different energies can be accelerated in the same drift tube. Instead of a single long linac, the CEBAF machine consists of two much shorter linacs and the beam from one is bent and passed through the other. This can be repeated for up to four cycles. Even with the radiation losses inherent in bending the beams, very intense beams can be produced with energies between 0.5 and 6.0 GeV. CEBAF is proving to be an important machine in the energy region where nuclear physics and particle physics descriptions overlap.